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Real Time Implementation of Cartesian Space Control for Underactuated Robot Fingers

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***Abstract*— This paper presents a real time implementation of a sliding mode controller (SMC) for the underactuated BERUL[1] fingers. The use of SMC is to deal with the inaccuracies and unmodelled nonlinearities in the dynamic model of the robotic fingers, in particular, to overcome significant friction and stiction. This paper in particular shows a practical implementation of Cartesian space control for the BERUL fingers. For the purpose of comparison, the performance of the PID controller is included in this paper. The main controller for positioning control is the combination of a feedback linearization (FL) scheme and SMC. The results show that the SMC performed better than the PID controller in the Cartesian space control.**

***Index Terms*— Robot Fingers, Sliding Mode Controller, PID Controller, Cartesian Space Control**

I. Introduction

Various techniques have been proposed to grasp an object for robot fingers. According to Montana [1], we can divide the general approaches to robot fingers manipulation into two categories, those which focus solely on velocity and those which deal with configuration-space issue. He further describes the velocity based approaches into four categories namely purely kinematic control, dynamic control, control the location of the object and control the position of the point of contact. A purely kinematic control means that the state of the finger plus object system is completely determined by the state of the finger joints. In contrast to the kinematic control, the dynamic control means that the state of the full system depends on dynamics quantities as the state of the finger joints. The location of the object reflects to the center of its own body whilst the position of the point of contact implies the contact surface of its own body. In general, previous work on velocity-based control can be found in Montana [2, 3, 4, 5] and Hunt et al. [6]. On the other hand, we can define the configuration space as the space of possible positions that a robot finger system may attain. Thus, this requires the set of all legal combinations of finger joint angles and contact states of an object. Some work on the configuration space issue can be referred to are in Fearing [7], Hong et al. [8], Li and Canny [9] and Brock [10].

Hence, to investigate a grasping performance for the BERUL fingers, a velocity based approaches as mentioned above is considered. The robust control technique i.e. a sliding mode controller (SMC) is used to overcome friction and stiction. It is to note that the BERUL fingers are significantly affected by stiction. The work in [11, 12, 13, 14] has been suggested to overcome friction and stiction where an adaptive controller was

[1] The mechanical design and manufacturing for the BERUL hand has been conducted by Elumotion (www.elumotion.com).

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employed. Moreover, a new control approaches via a Nominal Characteristic Trajectory Following (NCTF) [15] was proposed mainly to overcome friction and stiction for the BERUL fingers. The results have shown that the NCTF produced lower total signal energy as compared to the adaptive control. However, the controller has not been tested experimentally for the robot fingers. It is important to show that the grasping can be achieved in real time. In this work, a well known sliding mode controller (SMC) is proposed and investigated. The implementation of the SMC is carried out based on the forward kinematics as provided in [16]. Having found the forward kinematics of the BERUL fingers, the Cartesian space control can be introduced.

The kinematics of the manipulators contains position, orientation, and velocity analysis of manipulators which can be exploited for tracking and grasping of the BERUL fingers. For this, the Jacobian of the forward kinematics has been deployed in order to implement a Cartesian coordinate space control. Specifically, the Jacobian can be described as the configuration of the finger changes while in motion, the mapping of velocities changes accordingly. Having the kinematics of the BERUL fingers, the Cartesian coordinate space control can be achieved by employing Sliding Mode Control (SMC) [17]. At this point, the Jacobian is also used for mapping of forces and torques where the set of joint torques are required to generate the force and moment at the end-effector. The success in the Cartesian coordinates control will lead to the implementation of a compliance control in a cylindrical coordinate system in future. In general, this paper is organized as follows. Section II focuses on the summary of the kinematics of the BERUL fingers. Section III introduces controller design for which the Sliding Mode Controller (SMC) is employed to alleviate nonlinearities. Section IV illustrates the experimental set up, Section V discusses the tracking performance and followed by conclusions in Section VI.

II. Forward Kinematics Analysis

It is very important to show that a sufficient forward kinematics of the BERUL hand is obtained. A simple way of modeling kinematics is by using the Denavit Hartenberg (D-H) representation. The D-H technique allows us to use a systematic approach for deriving the forward kinematics in particular for complex transformations which consist of several joints and links. In brief, the following forward kinematics is obtained (see Figure 1) for the end-effector (i.e. [X, Y, Z]):

$$X = a_1 \cos\theta_1 + a_2 \cos(\theta_1 + \theta_2) \tag{1}$$

$$Y = a_1 \sin\theta_1 + a_2 \sin(\theta_1 + \theta_2) \tag{2}$$

$$Z = 0 \tag{3}$$

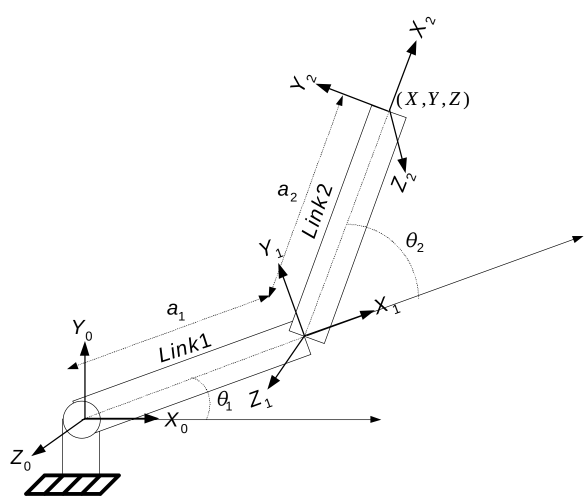


Figure 1. Derivation of forward kinematics for two links robot manipulator by using DH technique

Moreover, we can also derive the kinematics Jacobian from equations (1) and (2) as follows:

$$\frac{\partial X}{\partial \theta_1} = -a_1 \sin\theta_1 - a_2 \sin(\theta_1 + \theta_2) \quad (4)$$

$$\frac{\partial Y}{\partial \theta_1} = a_1 \cos\theta_1 + a_2 \cos(\theta_1 + \theta_2) \quad (5)$$

$$\frac{\partial X}{\partial \theta_2} = -a_2 \sin(\theta_1 + \theta_2) \quad (6)$$

$$\frac{\partial Y}{\partial \theta_2} = a_2 \cos(\theta_1 + \theta_2) \quad (7)$$

$$\frac{\partial Z}{\partial \theta_1} = 0 \quad (8)$$

$$\frac{\partial Z}{\partial \theta_2} = 0 \quad (9)$$

Similarly, the forward kinematics of the BERUL fingers can be easily derived by using the D-H technique. A sufficient of the forward kinematics of the BERUL finger has been shown in [16]. Apart from using D-H technique, Jalani [16] also introduced a new technique via Roborealm to obtain a sufficient forward kinematics of the BERUL fingers. The forward kinematics results obtained in [16] can be practically used for positioning control in the Cartesian space. Subsequently, the Jacobian can be easily obtained once the forward kinematics is available.

III. Controller Design

The structure of the proposed controller for the BERUL fingers is shown in Figure 2. The function of the controller is to control the finger position for example X coordinate so that it moves to the desired position X_d.

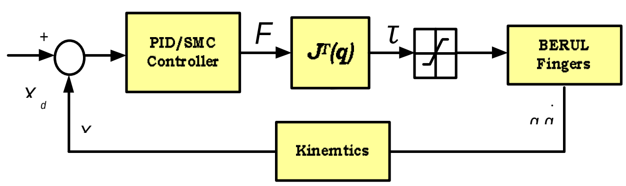


Figure 2. The structure of the proposed controller

For controller design, the model

$$\ddot{q} + f = u \quad (10)$$

is considered, where m is the generalized mass/inertia, f is a lumped expression for the major nonlinearities i.e. gravity, friction and centrifugal/coriolis force.

A. Sliding Mode Controller (SMC)

Motivated by the recent development of the SMC on a two-link rigid robotic manipulator through simulation [18], the same controller is applied for the BERUL fingers. Using the general dynamic equation of (10), a suitable sliding mode controller [18] is designed as follows. The joint torque vector τ can be split into two additive terms:

$$\tau = \tau_0 + \tau_1 \quad (11)$$

where $m_0(q)$, $f_0\ (q, \dot{q})$ are the nominal value of $m(q)$ and $f(q, \dot{q})$ respectively; which are defined as $m_0(q) = m(q) - \Delta m$ and $f_0(q) = f(q) - \Delta f$; $K_P \in R^{nxn}$ and $K_D \in R^{nxn}$ are positive scalars determining the closed loop performance; and the tracking error is defined as $q_e(t) = q(t) - q_d(t)$ with $[q_d(t)\ \dot{q}_d(t)\ \ddot{q}_d(t)]$ being the reference trajectory and its time derivatives. Note that τ_0 represents the computed torque component and τ_1 denotes a discontinuous torque control. The discontinuous torque control and sliding manifold are respectively defined as

$$\tau_1 = \tau_0 sign(s) \tag{12}$$

$$s = \dot{q}_e + K_s q_e \tag{13}$$

In order to control the effect of the chattering, the following term is used,

$$\frac{s}{s + |\delta|} \tag{14}$$

instead of $sign(s)$ where δ allows to suppress chattering.

B. PID Controller

For the purpose of comparison, a PID control scheme is adopted from Ge et al. [14] and Jalani et al. [15]. Then, the control input term (from equation (14) as given in [15]) can be simplified as follows.

$$u = k_1 + k_i \int_0^t r dt \tag{15}$$

where k_1 represents a proportional gain and k_i represents an integral gain. Note that, using r from equation (11) as given in [15], the control in (8) is indeed a PID controller.

C. Cartesian Space Control

The derivation of the robot finger kinematics as elaborated in Section 2 allows us to express the finger position in the Cartesian coordinates. For example, the position $x = x(q)$ of the thumb finger can be uniquely computed as a function of q where the relationship can be expressed in Cartesian velocities and accelerations respectively as

$$\dot{x} = J\dot{q} \tag{16}$$

$$\ddot{x} = \dot{J}\dot{q} + J\ddot{q} \tag{17}$$

J is the Jacobian of the kinematics $x = x(q)$ i.e.

$$\tau_0 = m_0(q)(\ddot{q}_d - K_D\dot{q}_e - K_P q_e + f_0 (q, \dot{q})), \tag{18}$$

The obtained Jacobian will be used for the following applied torque

$$u = J^T F \tag{19}$$

where F is the actuator of the finger. This implies that the dynamics of (10) can be rewritten as:

$$J^{-T} m J^{-1} \ddot{x} - J^{-T} m J^{-1} \dot{J} \dot{q} + J^{-T} f = J^{-T} u \tag{20}$$

or

$$\widehat{m}\ddot{x} + \hat{f} = F \tag{21}$$

where

$$\widehat{m} = J^{-T} m J^{-1} \tag{22}$$

and

$$\hat{f} = -J^{-T} m J^{-1} \dot{J} \dot{q} + J^{-T} f \tag{23}$$

and

$$F = J^{-T} u \tag{24}$$

This new model allows the sliding mode approaches of Shi et al. [18] to be used.

IV. Experimental Setup

For the real time implementation of the control scheme, a dSPACE DS1106 embedded system is employed. The Simulink model of the scheme is compiled into real-time C code and run in the dSPACE system. A sampling time of 1 millisecond is used. The BERUL fingers use optical encoders for position and velocity.

Each joint is equipped with a Maxon EPOS programmable digital motor controller. All the sensors and actuators of each joint are connected to the EPOS positioning controllers, which communicate with dSPACE via a CAN-Bus and provide the low-level current control for torque demands with the brush-less DC motors. A multi-step demand is applied in y and z direction. In general, Figure 3 shows the experimental setup for the BERUL fingers.

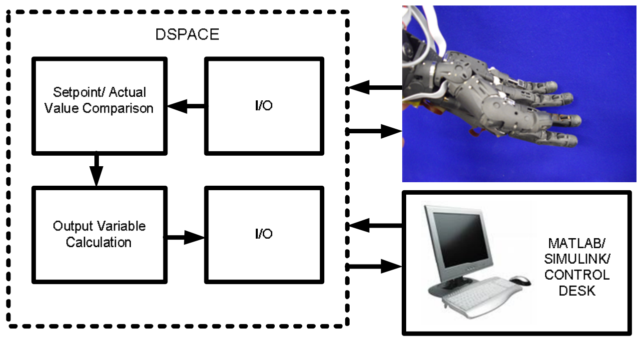


Figure 3. Experimental setup for the BERUL fingers

V. Tracking Performance

Based on a given workspace as shown in Figure 4, the tracking in Cartesian space is practically illustrated in y direction for index, middle, ring and small fingers. In contrary, the thumb is practically depicted in either x and/or z direction.

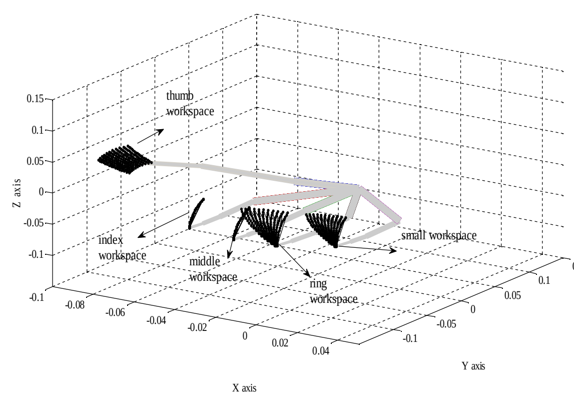


Figure 4. Workspace for the BERUL fingers

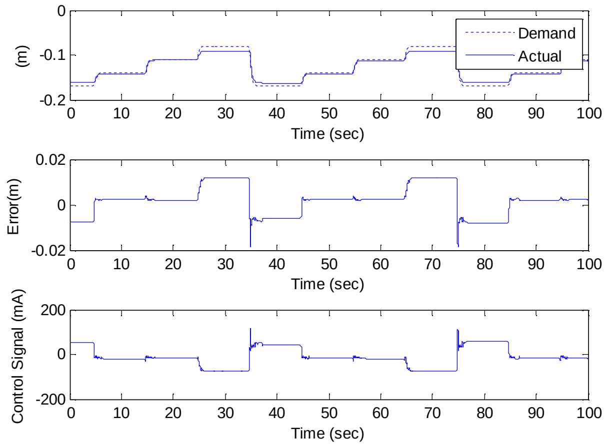
Here, only ring and thumb fingers are practically shown in Cartesian space control. Generally, the results show that the PID and the SMC follow a required trajectory satisfactorily as shown in Figure 5(a), Figure 5(b), Figure 6(a) and Figure 6(b) respectively. The detailed performance from each controller can be seen by using a quantitative measure of performance as indicated by [19] and [20] which is computed as follows:

$$Normalized\ Error = \sum_{i=0}^{N_s} |ydi - yi| / N_s \tag{25}$$

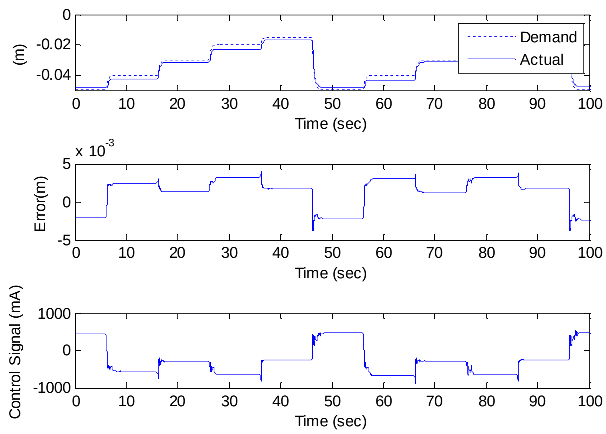
while we also consider

$$Normalized\ Error = \sum_{i=0}^{N_s} |u_i|^2 \tag{26}$$

where ydi is the demand signals, yi is the output signal, N_s is the number of samples and u_i is the control signal.

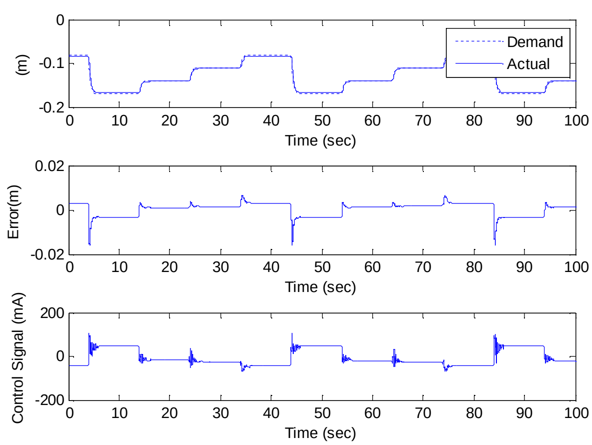


(a)Ring finger for y position

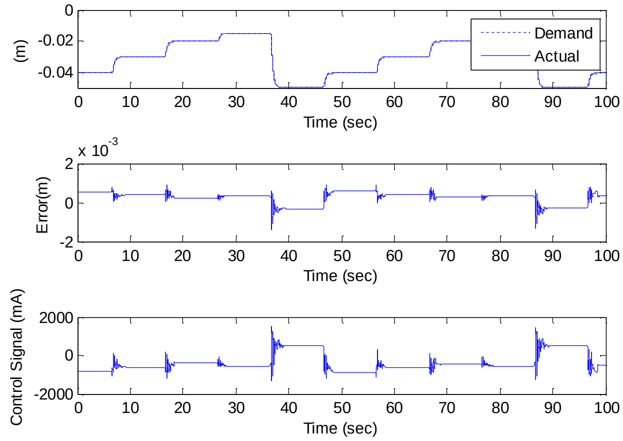


(b)Thumb finger for z position

Figure 5. Cartesian Space Control for PID



(a)Ring finger for y position



(b)Thumb finger for *z* position

Figure 6. Cartesian Space Control for SMC

TABLE I. NORMALIZED ERROR AND TOTAL CONTROL ENERGY FOR THUMB AND RING FINGERS

Finger	Controllers	Normalized Error (rad)	Total Control Energy (mA)
Thumb	PID	0.0022	2.2184×10^5
Thumb	SMC	3.7260×10^{-4}	3.6717×10^5
Ring	PID	0.0054	1.9231×10^3
Ring	SMC	0.0026	1.3934×10^3

It is found that the SMC has the smallest normalized error for the thumb and the ring finger. However, the PID controller uses smaller total control energy for the thumb finger and the SMC controller produces smaller total control energy for the ring finger. The details of the error signal and total energy produced by each controller can be referred to in Table 1.

VI. CONCLUSIONS

In this paper, the kinematics of the constrained underactuated BERUL fingers is used for Cartesian space control. It has been shown that the Cartesian space control was successfully demonstrated in real time implementation. In addition, the SMC is important to overcome the nonlinearities and uncertainties in particular friction and stiction which are emanated from the BERUL fingers. It is found that the SMC provides better normalized error for the ring and the thumb finger. However, the total control signal energy is slightly higher for the thumb finger.

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